HIGH FIDELITY COMPUTER SIMULATIONS FOR INDEPENDENT VALIDATION OF MISSION PLANNING PRODUCTS FOR TOMAHAWK CRUISE MISSILES

Gurmukh D. Mehta, Brian Greene, and Michael D. Eddings
Science Applications International Corporation
1213 Jefferson Davis Highway
Arlington, Virginia 22202

Abstract

This paper discusses the development, and current usage of independently developed, high fidelity simulations that have been used to evaluate the performance of Tomahawk cruise missiles for over 12 years. Two simulations comprise the core of a suite of analysis tools, that are collectively called the Mission Validation System (MVS).

MVS has been used for practically all vital mission analysis functions for Tomahawk Block II and Block III cruise missiles. These not only include OFS validation, pre-flight and post-flight OTL analyses, independent validation of mission data and other mission planning products, failure analysis, but also post-flight reconstruction analysis of all Tomahawk tactical strikes during the last five years starting with the first tactical use of Tomahawks in Desert Storm. Representative data from these analyses both for OTLs and the actual tactical strike in Bosnia are presented in the paper.

In light of impending Block IV missile upgrade, these models are being reviewed for enhancement to meet the future needs of the program without compromising quality or current capability. Specific approaches as to how to upgrade these simulations, with their respective merits, are also discussed in the paper.

Acronyms

AGR	Anti-jam GPS Receiver
BDA	Battle Damage Assessment
CMGS	Cruise Missile Guidance Set
CMP	Cruise Missiles Project
DOF	Degrees of Freedom
DSMAC	Digital Scene Matching Area Correlator
DTED	Digital Terrain Elevation Data
FOT&E	Follow On Test and Evaluation
HWIL	Hardware in the Loop
ISNSA	Independent Software Nuclear Surety Analysis
MDAC	McDonnell Douglas Aerospace Corporation
MVS	Mission Validation System
NAMCA	Navigation and Mission Computer Assembly
OES	Operational Embedded Software
OFS	Operational Flight Software
OFSSIM III	OFS Simulation for Block III missile
OFSSIM IV	OFS Simulation for Block IV missile
OPTEVFOR	Operational Test and Evaluation Force
OTL	Operational Test Launch
PEO(CU)	Program Executive Officer for CMP and UAV Joint Projects
RLS	Register Level Simulation
SAIC	Science Applications International Corporation
SDL	Satellite Data Link
TES	Tomahawk Engineering Simulation
TERCOM	Terrain Contour Matching
TLAM	Tomahawk Land Attack Missile
TMVS	Tomahawk Missile Verification Simulation
TWS	Tomahawk Weapon System
VEM	Vehicle Environment Module
WPC	Washington Planning Center

I. MVS Background

The MVS is a suite of simulations resident at the Washington Planning Center (WPC) of PEO(CU). It consists of (1) a Register Level Simulation (RLS) that interfaces with a 6-degree-of-freedom (6-DOF) missile Vehicle and Environmental Model (VEM), (2) a much faster 6-DOF FORTRAN simulation of the Block III OFS (OFSSIM III), and (3) a user interface system that combines a number of data processing and conversion tools to facilitate and automate inputs and outputs from these simulations. These simulations are non-proprietary; funded, managed and operated by the Cruise Missiles Project in Government-controlled spaces at WPC.

The Tomahawk Missile Verification Simulation (TMVS) uses a Register Level Simulation (RLS) of the Tomahawk Cruise Missile Guidance Set (CMGS). TMVS was originally designed for the Independent Software Nuclear Surety Analysis (ISNSA) of the Operational Flight Software (OFS) for the nuclear variant of Tomahawk Cruise Missiles back in 1983. Since then it has been upgraded for all land-attack variants of Tomahawk cruise missiles. A version of this simulation has been used for independent validation of every OFS released to the fleet. Over the years, this simulation has also been used for the independent validation of mission planning products, pre-flight evaluation and mission rehearsal, post-flight analysis, anomaly investigation of Operational Test Launches (OTLs) and post-flight strike reconstruction analysis of all Tomahawk tactical strikes during the last five years for the Cruise Missiles Program.

The Tomahawk Engineering Simulation (TES) of MVS, uses a FORTRAN simulation of the Operational Flight Software (OFSSIM) with the 6-DOF VEM. The use of a structured OFSSIM (vs. modeling of a set of Guidance equations) gives TES a distinct advantage over the traditional open-loop simulations. Though of slightly lower fidelity, MVS/TES is a very useful tool for the parametric and Monte-Carlo analyses of missile performance because of its computing speed and flexibility in use. This simulation can also be used for simulating Tomahawk strikes with multiple missiles in air.

Major components of the MVS suite of simulations, including the inputs/outputs, shown in Figure 1, are discussed below.

<u>Register Level Simulation (RLS)</u>

The RLS - core of the TMVS - is an all software Enhanced Register Level Simulation of the cruise missile's guidance set (CMGS) computer. It emulates the instruction set of the CMGS processor (LC4516c) in a simulated 64K memory and its 16 temporary registers. The opcode execution time is recorded in nanoseconds from an average instruction time provided by the manufacturer, Litton Corporation. The simulation executes the actual binary flight code and performs the 16-bit fixed point arithmetic as the actual computer on-board the missile. The RLS was originally coded in FORTRAN; the current version, which runs about 2 times faster than real time, is programmed in C.

<u>OFS Simulation (OFSSIM)</u>

In TES simulation, the CMGS and the resident flight code is simulated by the FORTRAN simulation (OFSSIM) of the actual OFS. It is derived from the actual OFS binary code and not just the performance specification. This provides a very fast execution of the missile guidance processor, while maintaining the processor's internal timings at 64-Hz rate. This high level simulation provides flexibility and fast analysis of missile performance under different input conditions.

<u>Vehicle and Environment Model (VEM)</u>

Both TMVS and TES simulations share a common Vehicle and Environment Model (VEM). It is a 6-DOF simulation of the missile airframe and its environment. Its basic function is to receive commands (e.g., fin, throttle, and platform torque commands, etc.) from the OFS, simulate the vehicle response to the commands, and return the sensor data (e.g., temperature, pressure, accelerometer data, radar data) back to OFS. Major subsystems of VEM are Fin Actuators, Propulsion, Airframe Dynamics, Inertial Platform, Airframe Kinematics, Mass and Inertia, Gravity, Air Data System (ADS), Atmosphere/Winds, Terrain/Radar Altimeter, etc. VEM is updated every 64th of a second and it provides updates to the CMGS simulation, via a shared interface.

<u>Launch Platform and Missile Components (GPS, DSMAC) Models</u>

These models simulate all the interfaces to the LC4516c flight computer. These include a 16-bit MK82 serial interface, Radar/Telemetry serial interface and all Mission Control Module (MCM) and other digital, analog and discrete interfaces. These are stand-alone independent models that execute at discrete intervals, unlike VEM that executes at a fixed 64-Hz rate. Recently, two independent models, the GPS Reference model and the First-Return Radar Altimeter model, both developed by MDAC, have been added to the simulations.

<u>User Interface and Support Programs</u>

The user interface and support tools combine a number of data processing and conversion tools to facilitate and automate inputs and outputs from the simulations. These tools, which have been developed over many years, are used to process data from a very large number of OTL and tactical missions, and to provide independent quality control checks on mission data products. These tools include conversion routines that allow the use of standard data products, help in the efficient detailed analysis of large data including graphical displays in color, and provide a summary of simulation results in a ready useable format.

II. Functional Capabilities

MVS simulations provide full Tomahawk TLAM flight simulation capability, from power-on, through alignment, boost, cruise over Digital Terrain Elevation Data (DTED) to the terminal processing at the target. It includes enroute TERCOM, GPS and/or DSMAC position updates depending upon the mission and missile features.

The RLS simulation uses the actual fleet-released compiled assembly-level OFS code together with the actual mission data in the same format as it is loaded across the MK82 interface by the TWCS into missile flight computer.

RLS with a high-fidelity 6-DOF VEM (running at a 64-Hz rate) is a closed-loop simulation that provides a unique capability to evaluate missile performance, quality of mission data and OFS/mission data compatibility in a laboratory facility. Comparison of simulation results with the performance data shows that the timing of the individual instructions, discrete events and MK82 message traffic is highly accurate.

Because of significant improvements in the speed of computer processing during the last ten years, the current RLS simulation on a DEC-Alpha processor runs about 2 times faster than real time. The TES simulation on a TAC-3 (HP9000-755) platform runs about 16 times faster than real time.

Being all-software simulations in higher-order languages, these simulations are highly portable and are not limited to any particular hardware. At WPC these simulations run on both TAC-3 and DEC platforms. This ensures high throughputs for periods with very short turn-around time. Also, multiple copies of these simulations can be run simultaneously on a multi- processor computer. This, however, cannot be accomplished in a HWIL simulation. Because of the simulations' computing speed and automated analysis tools, the WPC facility can process a large number of missions in a matter of days.

Both TES and TMVS simulations can run a given mission on the nominal and off-nominal paths. Because of its fast execution speed and flexibility, the TES simulation is being expanded to run in the Monte-Carlo mode. This capability allows the analyst to run the simulation with a user-specified list of Monte-Carlo input variables

The user interface provides an automated procedure for initialization, run-time control, data capture, selective data display and/or modification through the use of a script processor. This also allows for an event control, stop, pause, restart and the checkpoint capability at any desired time or an event.

III. MVS Usage

Because of high fidelity, platform independence and design modularity, variants of the accredited MVS are being used at six distinct sites for supporting different elements of Tomahawk missiles. These include:

- Washington Planning Center,
- Naval Surface Warfare Center at Dahlgren,
- Naval Surface Warfare Center at Indian Head,
- Naval Air Warfare Center-Weapons Division at China Lake,
- Hughes Missile System Company at Tucson, and
- McDonnell Douglas Aerospace at St. Louis.

Brief descriptions about the kind of testing at these sites can be found in Reference 1. The rest of this section provides further insight into the activities that are currently supported by these simulations at WPC for the Command and Control Program office (PMA-281) of the Cruise Missiles Project.

Operational Test Launch (OTL) Support

At WPC, SAIC analyzes every OTL mission with MVS. Analysis includes a binary compatibility check, where the mission is simulated in the RLS with the fleet-released OFS. In addition, simulation data is used to verify that all mission planning guidance was followed, that planning system predictions used for planning the mission were valid and that any pre-launch flight constraints (that mission planners could not simulate on the planning system) do not adversely affect missile performance.

After every OTL, the telemetry data from the test flight is sent to the WPC for analysis by MVS. This data is used to replicate the initial and weather conditions for the simulation. Telemetry data is then compared to simulation results to verify simulation accuracy and to demonstrate actual missile/mission performance. Results of these comparisons, including any lessons learned from the analysis, are communicated to the mission planners at the planning sites on an annual basis.

IV&V Support

MVS is used as a simulation tool suite for Independent Verification and Validation (IV&V) of the mission planning software for PMA-281. Selected missions produced by the Mission Planning System are sent to the WPC for analysis by the MVS. This analysis includes normal binary compatibility testing with the required OFS, as well as testing of the specific, new features in a particular mission-planning software release. Any anomalies or shortcomings found during this testing are reported to the program.

OPTEVFOR

During OPEVAL of any TWS improvement, including mission planning and/or AUR software upgrade, MVS is used by a select group of analysts to perform trusted-agent analysis of the system improvements, prior to OPTEVFOR approving these for the fleet release. The depth and extent of this testing depends upon the nature of the improvements that are being introduced in the overall weapon system. During the FOT&E phase, MVS is used to test both the FOT&E-specific OTL missions, as well as a representative set of operational missions for analysis. Because of the very detailed information available to OPTEVFOR from MVS, they are able to reduce the number of required test flights and evaluate a much broader and more representative set of mission/missile data; achieving an inexpensive but comprehensive test of all TWS subsystems prior to the fleet release.

Tactical Analysis

In the post-Cold War world of CNN and live action warfare, no weapon program can afford to let preventable mistakes occur. To provide an independent evaluation of the quality of mission planning products, SAIC supports PMA-281 in using MVS as the final quality control check. Periodically, a set of representative operational missions are sent to WPC for MVS analysis. These sets undergo rigorous testing and evaluation and the results are summarized as a set of procedures and recommendations in a detailed report that is presented to the planning sites as lessons learned.

Additionally, every time this weapon has been used by the fleet against real targets, MVS has been used to undertake post-strike reconstruction analysis. Since there is no telemetry data from tactical missiles, MVS reconstructs the entire launch scenario from the available ship and other source data. Using this data, simulation results are compared to BDA data to verify reported accuracy and effectiveness of the weapon and to further improve the operating procedures for future usage. The results of these reconstruction analyses are communicated to the appropriate parties and the planning sites as lessons learned.

Anomaly Investigation

During the course of the actual missile flight and simulation, anomalous missile behavior has been observed. One of the important application of MVS simulation tool is its use in the identification of the cause of an anomalous behavior and in the development and testing of recommended solutions to eliminate any future occurrences of these anomalies. MVS has played a critical role in finding, understanding and/or providing a solution to almost every anomaly for the past 12 years.

The three components that make MVS simulations so useful in anomaly investigations are the VEM, the RLS/OFSSIM approach to modeling the guidance equations, and the dynamic user interface. The RLS/OFSSIM simulation of missile CMGS is a very useful tool for the analysts to step through the code line-by-line, if necessary. The scriptable user interface allows an analyst to recreate anomalous conditions, change input data, and stop and restart the simulation at any precise point in the mission. The combination of these simulation features together with an automated user interface make MVS a very effective tool to help analyze missile anomalies.

IV. Baseline IV Upgrade

Currently the TWS program is going through Baseline IV, Phase 1, improvements. The key features of this upgrade are a new Navigation and Mission Computer assembly (NAMCA); an improved Anti-jam GPS; 2-way in-flight communications with the missile, permitting real-time BDA and en-route flex capability using Satellite Data Link; and Tomahawk strike planning and coordination. This section discusses the status of planned enhancements to MVS simulations to support these TWS improvements.

New Navigation Computer

The most significant missile improvement under Block IV is the upgrade of the navigation computer. The current processor, LC4516c, has a 16-bit architecture, with a fixed-point real number representation, i.e., technology circa 1974. The Block IV TLAM will use the PowerPC603 chip, a 64 bit architecture with instruction and data caching, pipelined floating point units and a very high clock speed.

One of the first MVS enhancements will be the creation of a Block IV OFSSIM. The current OFSSIM was reverse-engineered from the LC4516c assembly code to FORTRAN to make it portable and understandable. The OFSSIM was designed to closely resemble the OFS to simplify the maintainability of the program and to help trace any changes in the OFS.

The Block IV OFS of the Operational Embedded Software (OES) is being written in Ada and cross-compiled to run on the PPC603 chip. Thus, during Block IV, the fleet-deployed OFS will be available in a higher level language. The Block IV OFS Ada source code will be linked with a new I/O model and the 6-DOF VEM to form TES for Block IV. The Block IV Ada source code (composed of the Navigation and Mission Control modules), together with the new I/O model, will be designated OFSSIM IV.

The TES will not be capable of executing the fleet-deployed binary OFS, even though the Ada source code for OFSSIM IV will be very close to the actual flight software. Compiled Ada code will produce a drastically different assembly/machine code as it is compiled on different platforms. This will be true even when the PPC603 runs another operating system.

To maintain the current capability of running the fleet-released binary code prior to each test launch, and for each OPEVAL activity, the two feasible approaches are discussed below.

The first approach is to develop a hardware-in-the-loop (HWIL) simulation using the navigation computer. A HWIL simulation using NAMCA will provide a real-time capability for running the fleet-released OFS. Analysis, however, will be limited to the data normally provided from an in-flight TLAM.

The second approach is to write an RLS of the PPC603. The RLS of the PPC603 will run slower than real time today. However, with the advancements in technology and improvements in the processor's speed, it is perfectly feasible that such a simulation can approach real time or near-real time in about 5 years. For historical perspective, when RLS was first designed in 1983, it was 150 times slower than real time; today it runs about 2 times faster than real time. Moreover, as in TMVS, an all-software simulation will allow access to virtually all variables in the OFS thereby providing a very detailed and high-resolution tool.

The relative merits of different approaches discussed are summarized in Table 1. A TES simulation that uses a Block IV OFSSIM together with a NAMCA in the loop (that can use the actual OFS binary code) is the best overall solution for the short term. The MVS design would allow for the addition of an RLS simulation in the future should this become feasible in terms of simulation processing speed.

Table 1. Comparison of Relative Merits of Different Simulation Approaches for MVS for Baseline IV Upgrade

OFSSIM IV (TES) on any Platform	**HWIL using NAMCA**	**RLS of Power PC603**
(-) High fidelity	Very high fidelity	Very high fidelity
Faster than real time	Real time	(-) Slower than real time
(-) Each OFS release requires a new OFSSIM	Uses the actual OFS	Uses the actual OFS
Not hardware dependent	(-) Hardware dependent	Not hardware dependent
Can access/analyze most variables	(-) Can access limited variables due to hardware constraints	Can access/analyze most variables
Suitable for parametric analysis; Debugger available	(-) Good for missile performance, less suitable for analysis	Suitable for parametric analysis; Debugger available
Allows multiple users	(-) One user	Allows multiple users
Least expensive to build and maintain	(-) Expensive to build* and expensive to maintain	Expensive to build, not expensive to maintain

* The program is buying more than one copy of this set-up for the missile development

Anti-jam GPS Receiver (AGR)

The Block IV missile will have a more robust anti-jam GPS receiver requiring more detailed simulation. The MVS enhancements could include an all-software model, similar to the one being used today for Block III, with a commercial signal-generator model.

Satellite Data Link (SDL)

The Block IV missile will have a SDL transceiver to provide for in-flight 2-way communications. In MVS, the SDL may be simulated by an all-software satellite communication model or via an integrated software/hardware model that uses the actual satellites for the message traffic.

Strike Planning Simulation Capability

In line with Baseline IV requirements and the experience gained from the tactical use of Tomahawk missiles, MVS simulations are being expanded to simulate a Tomahawk strike capability. Based upon the analysis of actual field data and the lessons learned during the last five years, the procedures for the deployment of this weapon have been greatly refined. One clear requirement that has emerged from this activity is the need to simulate and deconflict a number

of missiles in close proximity, both in space and time, approaching a particular area. MVS is being enhanced to allow the simulation of a multiple launch scenario under which the flight path data for each missile will be analyzed for interactions with other missiles in the strike. Logical extensions of this capability will include salvo-to-salvo deconfliction and missile interference in the terminal area with respect to target prosecution.

V. Testing and Accreditation

In 1991, both MVS/RLS and TES simulations were accredited for Block II and III missiles by the Simulation Management Board of the Cruise Missiles. In April 1996, these simulations were reaccredited for Tomahawk Block III PST enhancements. During the accreditation process, the simulations went through rigorous missile performance comparisons with the actual flight data and with the development contractor's hardware-in-the-loop simulations. The accreditation test plan[2] and the results of these comparisons are available in the final report[3] and other formal documents[4-6].

Because of high fidelity, ease of use and high dependability, MVS simulations are regularly used by COMOPTEVFOR for the operational testing of all major improvements to the weapon system before fleet release. Indeed, as a consequence of thorough testing and quality of performance prediction, MVS/RLS was the first simulation formally accredited by COMOPTEVFOR in 1994 for the Tomahawk Cruise Missiles Program.

Figures 2-4 demonstrate how well MVS simulation predictions match the telemetry data gathered from the actual flights. These plots have been extracted from the standard MVS analysis report that is generated for each OTL. Figure 2 shows the overall ground-track correlation of the simulation data with the telemetry data for OTL-193. The only differences are the ship-entered waypoints versus a simulated minimum stand-off launch. Figure 3 shows representative comparison of several critical flight parameters such as: 1) altitude, 2) vertical velocity, and 3) Mach number for OTL-193. Figure 4 shows the details of the atmospheric temperature modeling done by MVS for different day types. The top graph shows the correlation between the temperature sensed by the missile and the three day types modeled by the simulation. The bottom graph shows the missile's planned altitude profile. These plots demonstrate how well the atmosphere is modeled by the simulation. The quality of comparison with the flight data is further improved if actual environment conditions are factored in the simulations.

The accuracy and fidelity of MVS simulations make it logical to extend their predictions to tactical situations where telemetry data is unavailable. Figures 5 through 10 are from the Bosnia Strike (September 1995) Reconstruction Analysis[7] performed by the MVS Analysis Team. Figures 5 and 6 show a 2-D and 3-D perspective of the missile fly-out trajectories off the USS Normandy. Figure 7 demonstrates how well the launch-platform-induced Time-of-Arrival error is promptly corrected by the missile at the beginning of the flight. Figure 8 shows a detailed look at the trajectories of six missiles in the strike while performing a vertical update just before the terminal maneuver. Figures 9 through 11 provide details of the deconfliction logic invoked by the OFS for a Tomahawk strike.

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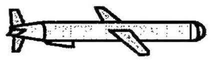


MISSION VALIDATION SYSTEM (MVS) AT THE WASHINGTON PLANNING CENTER

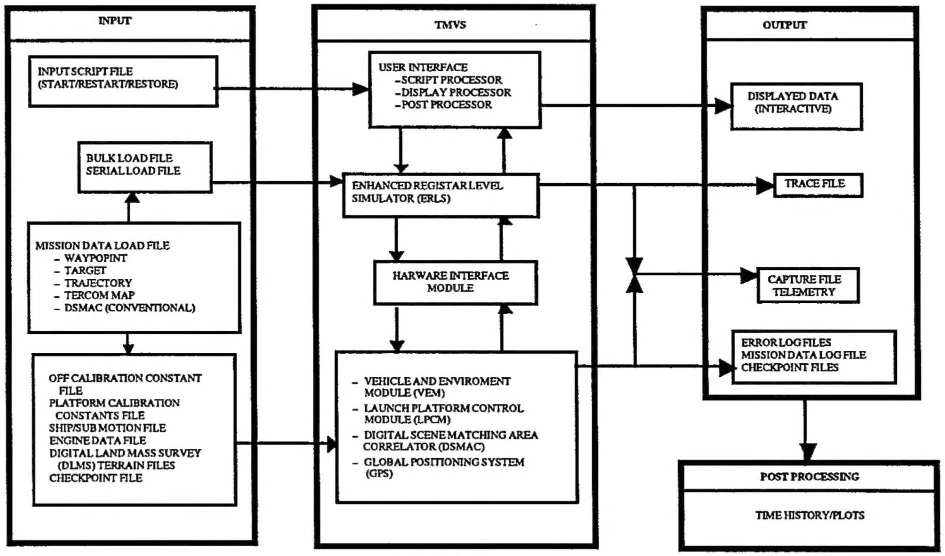


FIGURE 1

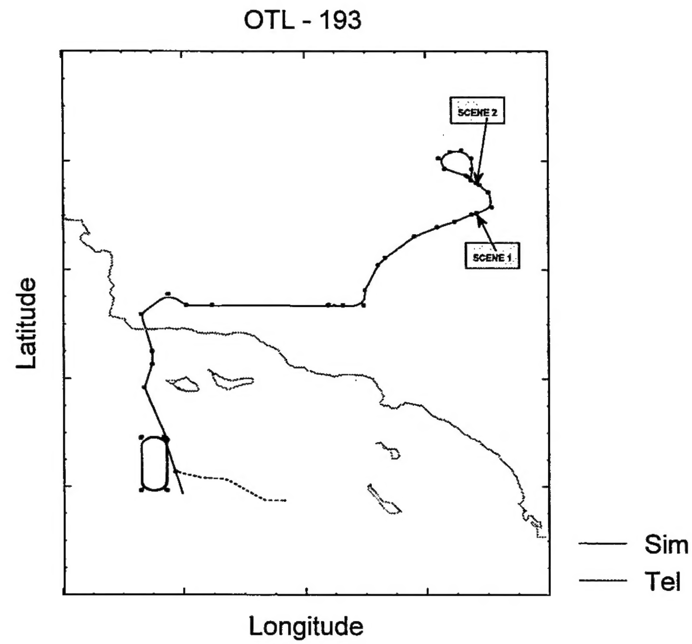
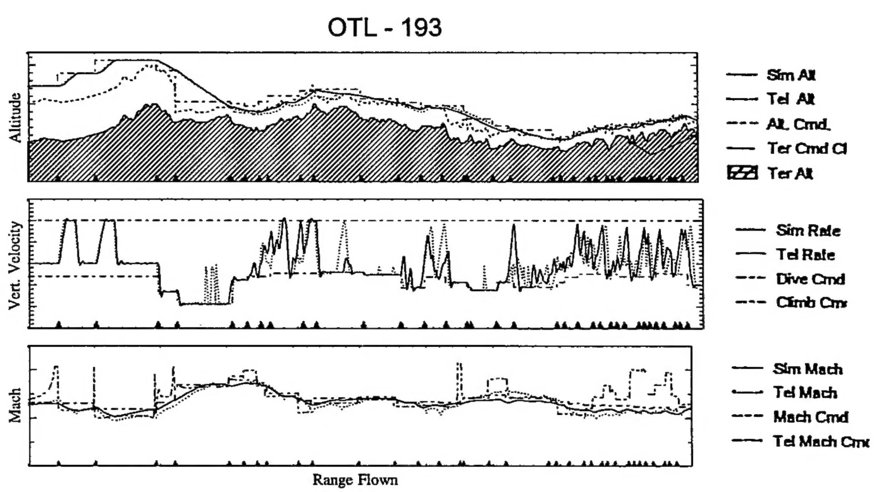


FIGURE 2



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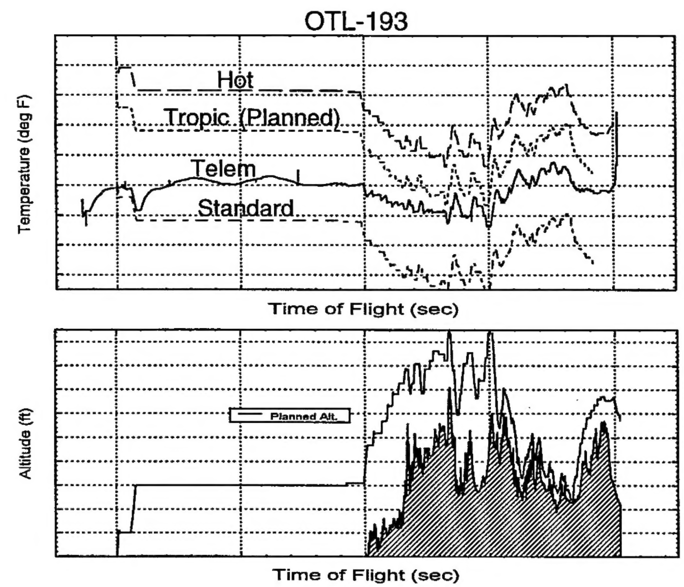

FIGURE 4

Flyout Profiles
Missiles 7 - 13

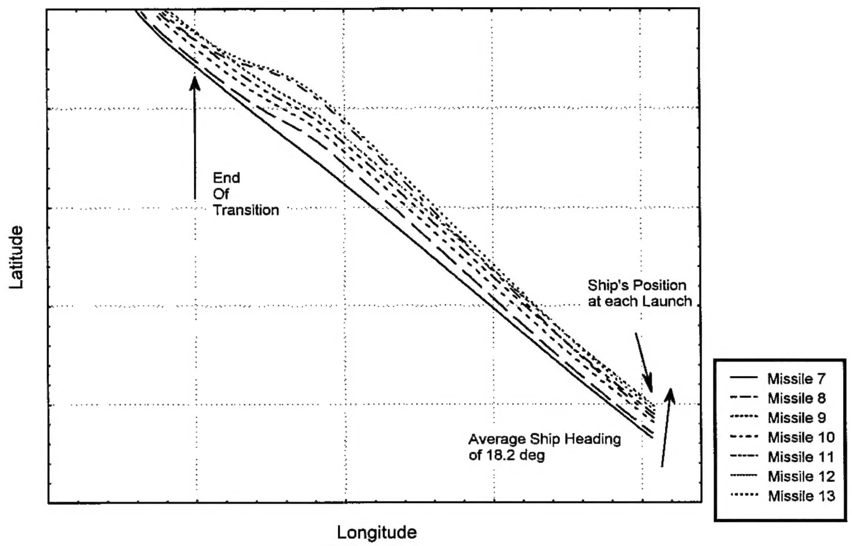

FIGURE 5

Flyout Trajectories
Missiles 7 - 13

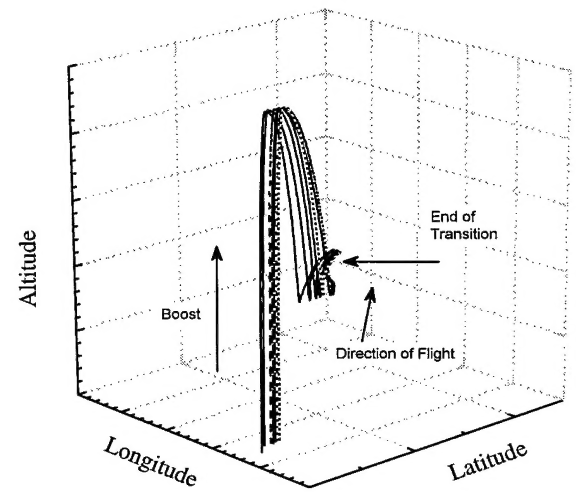

FIGURE 6

TOT Error Removal
Missiles 7 - 13

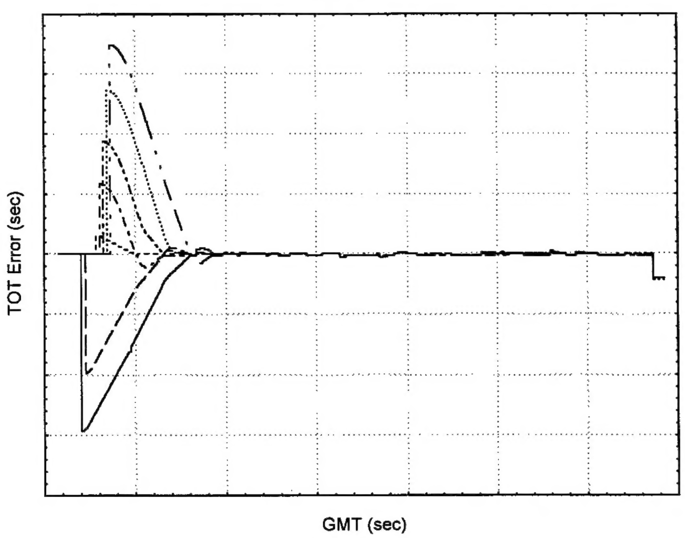

FIGURE 7

Vertical Update
Missiles 1 - 6

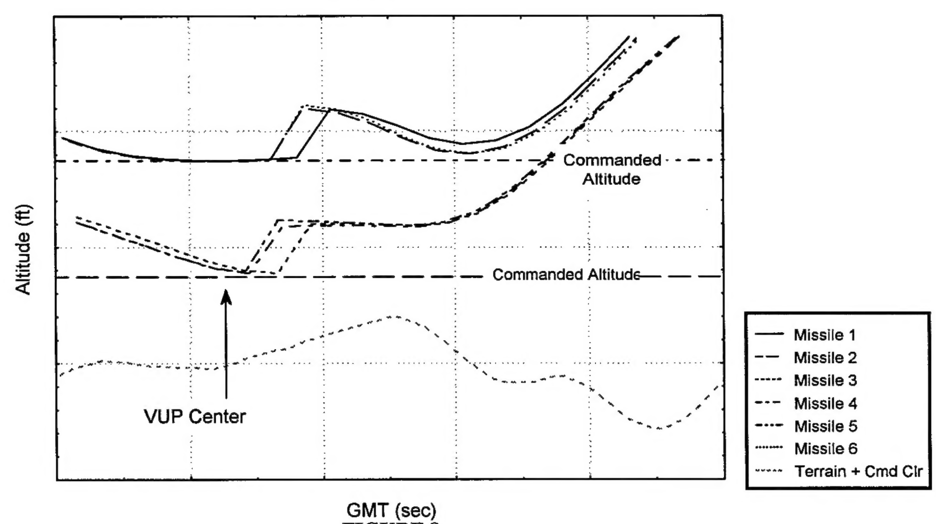

FIGURE 8

OFS Deconfliction Lane Layout

Lane 14	Lane 2 Missile 2 T+25	Lane 11 Missile 5 T+76	Lane 20 Missile 6 T+128	Lane 8 Missile 8 T+179	Lane 17	Lane 5 Missile 3 T+41
Lane 7 Missile 4 T+56	Lane 16 Missile 9 T+245	Lane 4 Missile 7 T+159	Lane 13	Lane 1	Lane 10	Lane 19 Missile 1 T0 Missile 10 T+241
Lane 0 Missile 11 T+256	Lane 9	Lane 18	Lane 6 Missile 13 T+289	Lane 15	Lane 3 Missile 12 T+273	Lane 12

FIGURE 9

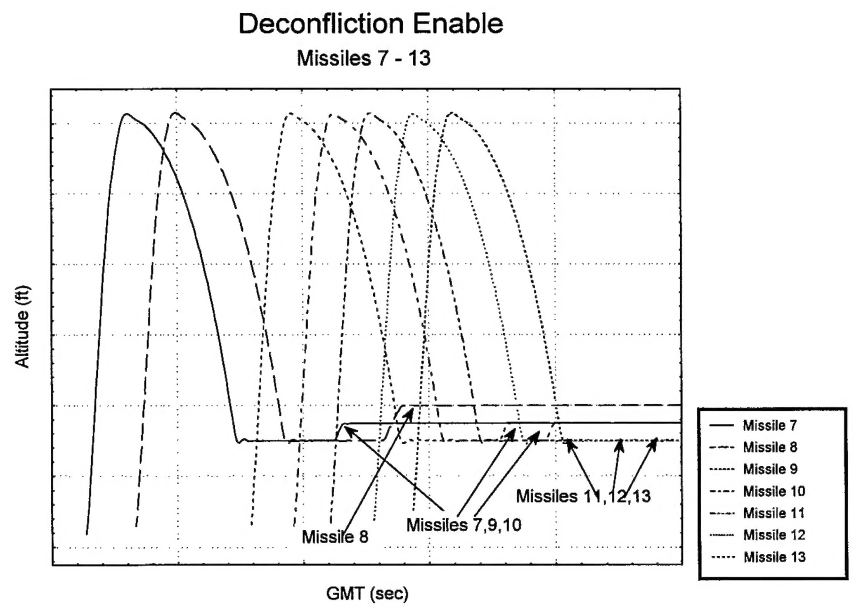

FIGURE 10

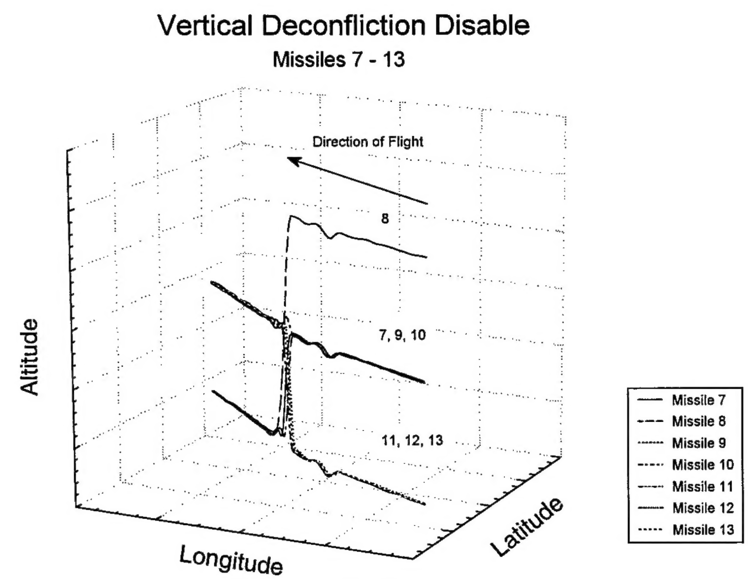

FIGURE 11

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